Investigation of soot particle properties in the combustion chamber and the exhaust gas pipe of a common-rail diesel engine under steady and non-steady operating conditions

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Due to the limited resources of fossil fuels engines with direct injection are of increasing interest because of their high fuel efficiency. However, particularly the combustion process in diesel engines leads to the formation of soot, part of which is emitted with the exhaust gas. Despite the decrease of absolute soot emission levels of modern Diesel engines it is possible that adverse health effects may increase, since it is believed, that sizes of the particles emitted from modern high pressure injection Diesel engines decrease. In particular fine and ultra-fine particles with sizes below 100 nm are of significant importance because they may penetrate into the respiratory tract.

To minimize the soot emission in real combustion systems information on the complex processes involved in the formation and oxidation of soot has to be obtained. From this information, appropriate models can be developed describing the formation and oxidation of soot. For the validation of these models experiments are necessary which yield data of soot particle properties, even under transient conditions.
For this purpose two different techniques have been applied in this work. On the one hand the extended two-color-method (2CM) has been used at one single cylinder of a four cylinder common-rail diesel engine. By means of an optical probe which is mounted in the glow plug hole the light emission of the glowing soot particles is transmitted via fiber optics to a detection system. Using an indicating system the light signals can be detected as a function of the crank angle and the soot concentration is computed by post processing. It yields a crank angle resolved signal of the soot concentration in the combustion chamber. On the other hand a combination of Rayleigh-scattering and Laser-Induced-Incandescence (RAYLIX) measurements have been performed simultaneously in the exhaust gas pipe of the same cylinder to obtain temporally resolved soot concentration, mean particle radii and number densities. The location of measurement has been placed as near as possible to the cylinder-head. An optical flange was mounted between the cylinder head and the exhaust manifold and a laser sheet of about 30 mm width has been launched perpendicular to the exhaust gas flow. Thus a two dimensional light section has been formed in the exhaust gas flow. The scattering and the LII signals can be detected by two intensified CCD cameras located perpendicular to the propagation of the laser beam. From the detected light signals soot particle properties can be obtained. Due to the short distance between the cylinder and the optical flange a comparison of the results obtained in the exhaust pipe and the cylinder is possible. Therefore, information about the oxidation of soot during combustion in the cylinder can be obtained. The results of these measurements were correlated with conventional techniques such as the opacity and the Filter Smoke Number (FSN) measurements in the entire exhaust gas. In contrast to time integral measurements like the FSN, the techniques used in these experiments yield information about soot particle radii and soot concentrations in the exhaust gas mainly for transient engine operation.

The simultaneous crank angle dependant measurements of RAYLIX, 2CM and the pressures in the combustion chamber and in the exhaust manifold show, that RAYLIX detects the soot directly after the exhaust valve opens.

For several steady state operating points it could be shown that the FSN, the opacity and the averaged LII signal correlate. Therefore the calibration of the relative LII-signals with the opacity measurements is possible.

Experiments have been carried out, varying the pilot injection quantity and the exhaust gas recirculation rate (EGR-rate). Comparison of the measured in-cylinder soot concentration and the emitted soot amount shows that decreasing in-cylinder soot formation does not necessarily result in a reduced amount of emitted soot.

To investigate the soot formation during transient conditions of the engine, the in-cylinder soot concentration and the concentration of the emitted soot in the exhaust gas at different load changes have been measured. Also the mean particle radii and the number densities of the emitted soot particles have been detected.
Several experiments of load changes with constant and non-constant engine speeds show similar behaviour regarding the soot concentrations, mean particle radii and number densities. The soot concentrations in the combustion chamber as well as in the exhaust gas rise continuously during load changes. Evaluations of the measured scattering signals show increasing number densities whereas the mean particle radii are decreasing while the load rises.

It can be said, that in the majority of cases higher engine speeds result in lower soot concentrations at different loads.
Load changes at higher engine speeds ($\geq$1800 rpm) do not show the sharp increases in the soot concentration detected at lower engine speeds.

Basically it can be ascertained that the soot concentrations in the combustion chamber and in the exhaust gas show a similar behaviour during load changes.

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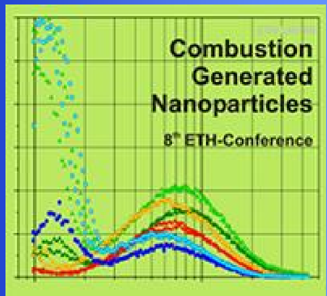

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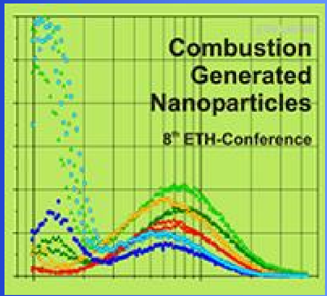

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  Load Changes with n=const. and n≠const.

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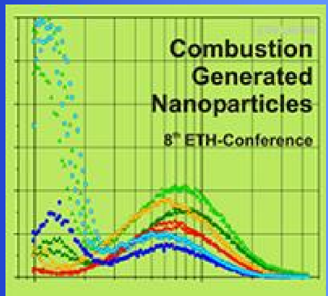
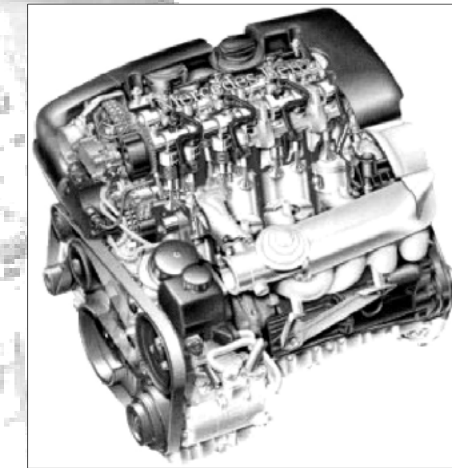


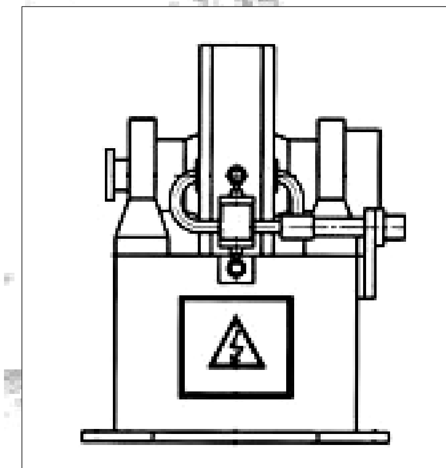
Experimental Set Up

Engine Test Bed, Standard Soot Measurement Techniques

Common-Rail-DI-Diesel Engine

Bore......................	88	mm
Stroke....................	88.4	mm
Number of Cylinders................	4	
Displacement Volume..................	2151	cm^3
Compression Ratio......................	19:1	
Nominal Power Output.........	92	kW
max. Torque (1800-2600 rpm)....	300	Nm





Standard Soot Measurement Techniques

- Filter Smoke Number (FSN)
- Opacity

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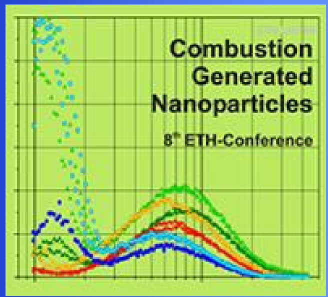
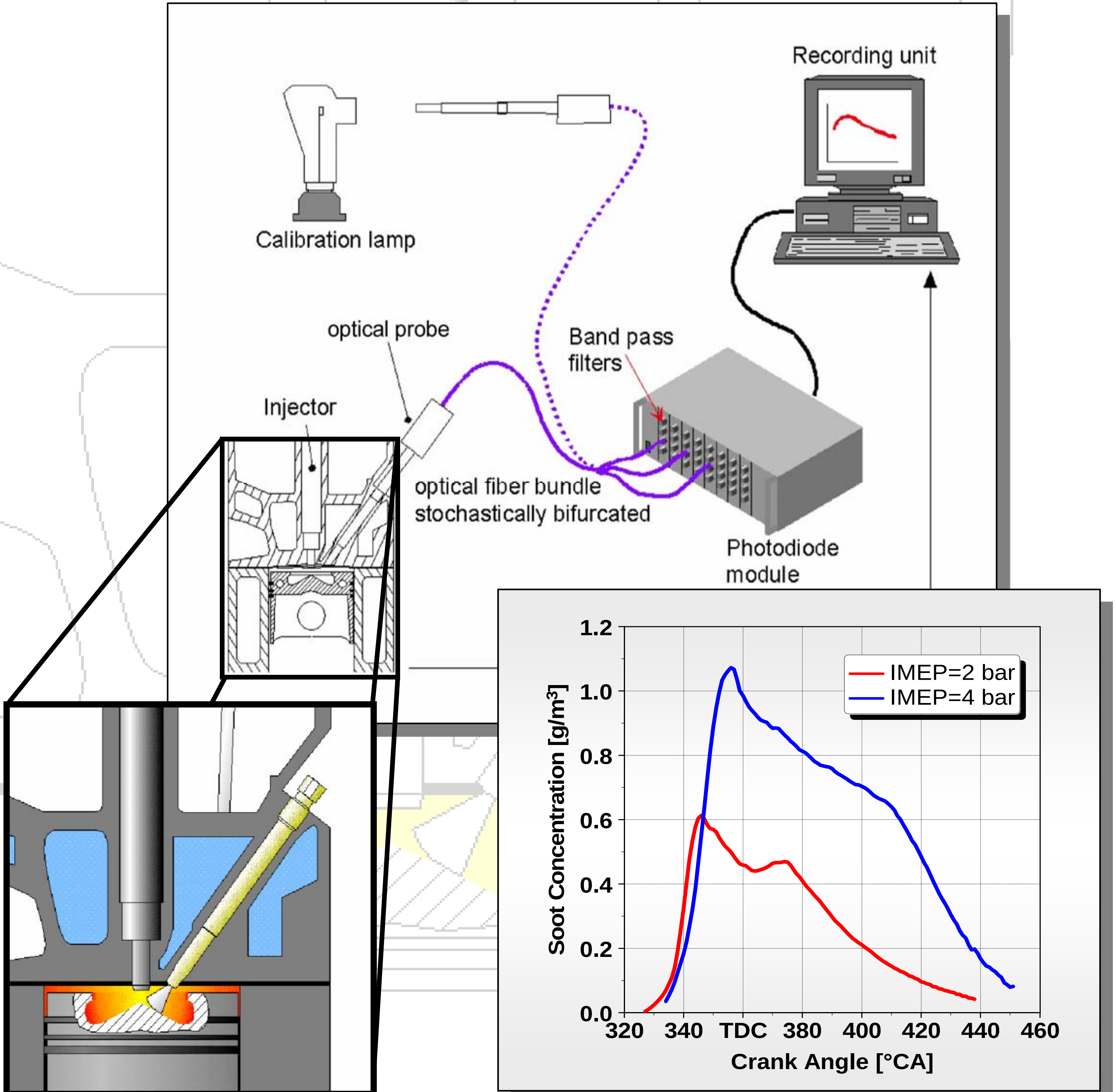


Experimental Set Up

In Cylinder Soot Concentration Measurement (2 Color Method)



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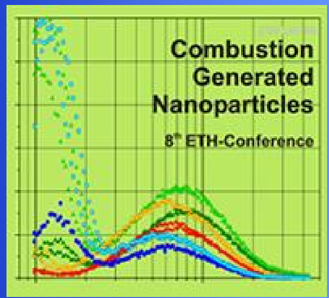
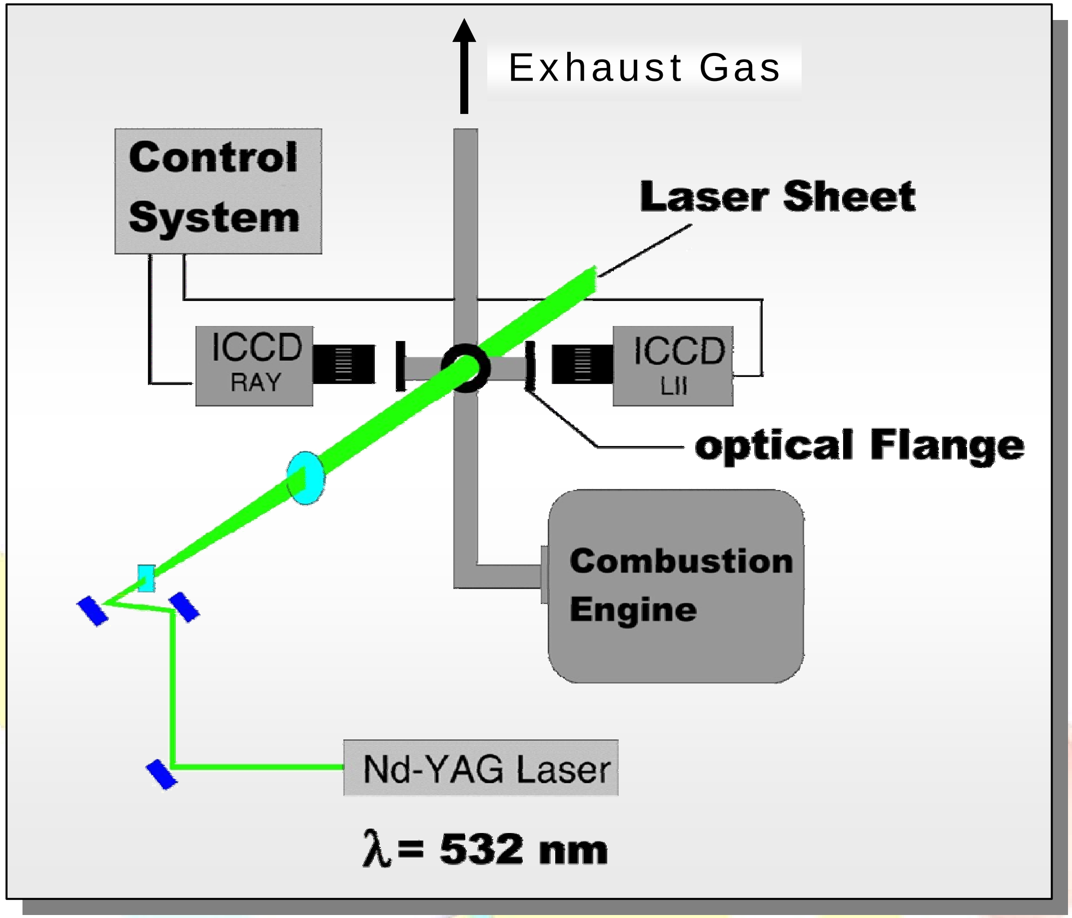


Experimental Set Up

RAYLIX
Technique
-Basic Set Up-



- Soot Volume Fraction f_v
- Number Densities N_V
- Mean Particle Radii r_m

high temporal and spatial resolution

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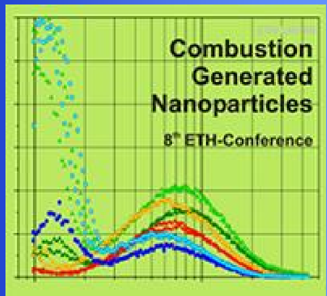

Experimental Set Up

RAYLIX Technique

Requirements:

- Point of measurement inside the combustion chamber
- Analysis of one cylinder

Problem:

- Due to lack of space it is not possible to apply RAYLIX in the combustion chamber of a production engine without significant modifications

Solution:

- Modifications in the exhaust gas system were necessary
- Design of an optical flange mounted directly at the cylinder head which enables the RAYLIX technique to be used as near as possible to the combustion chamber

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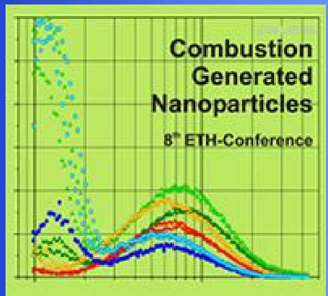
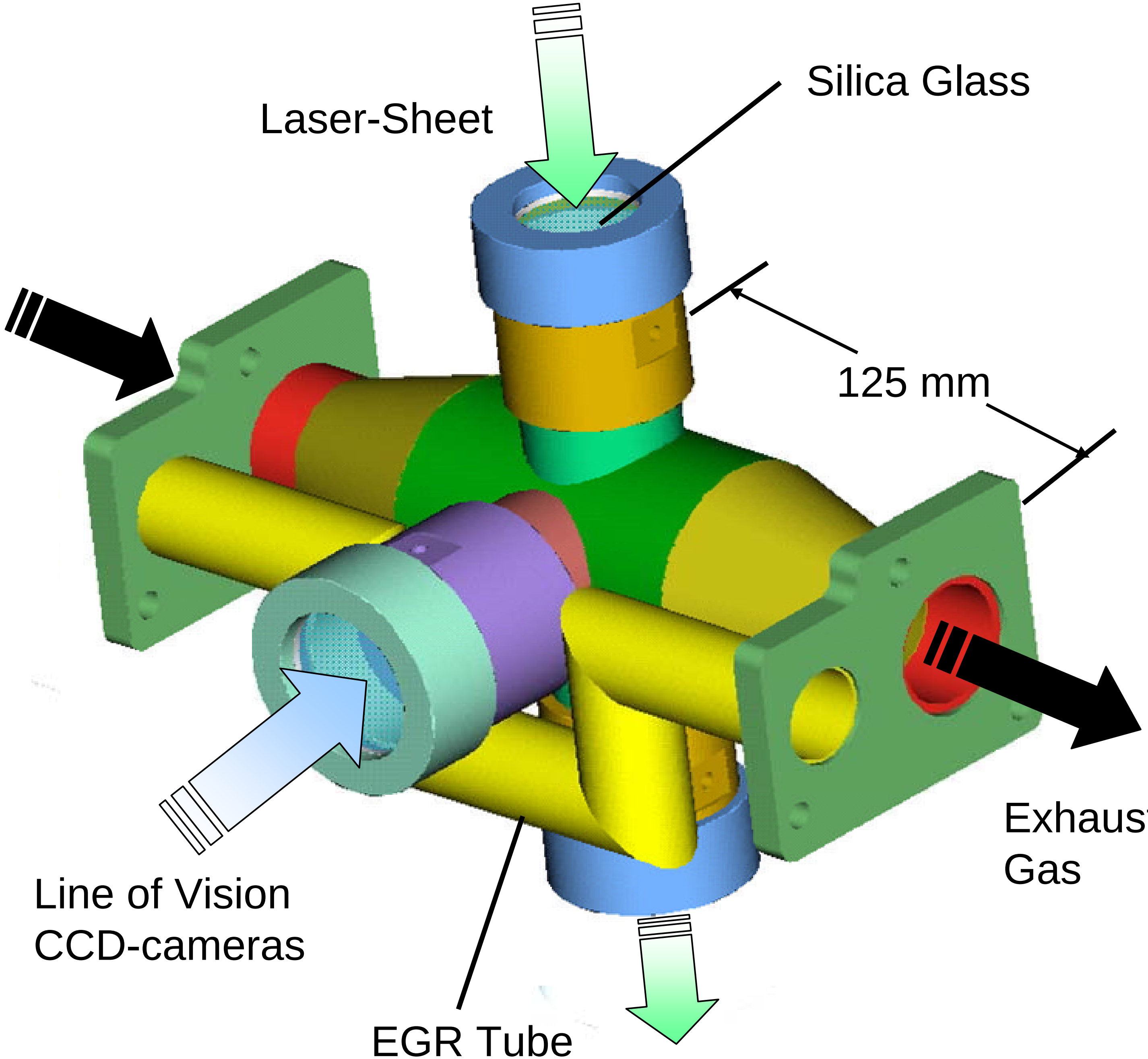


Experimental Set Up

RAYLIX
Technique
-Optical Flange-



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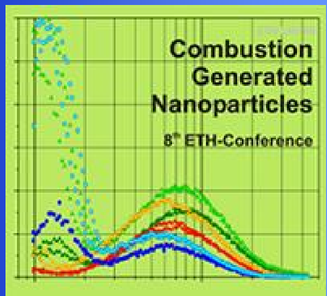
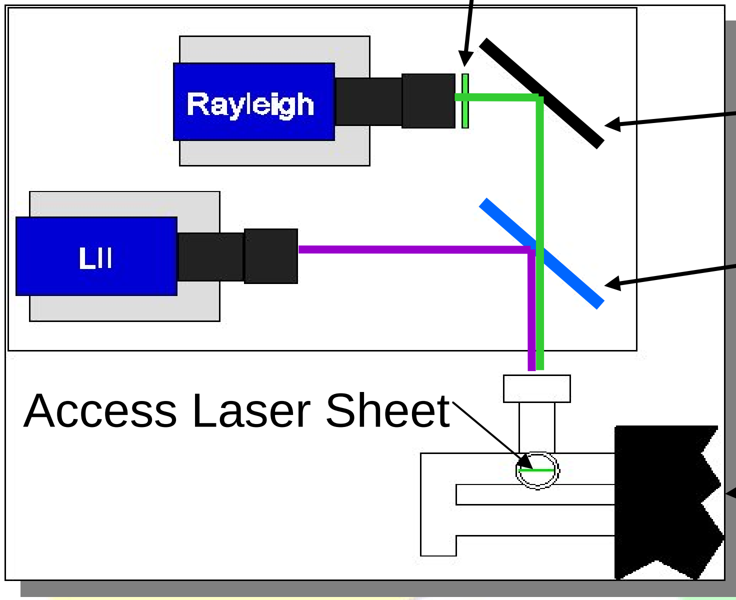


Experimental Set Up

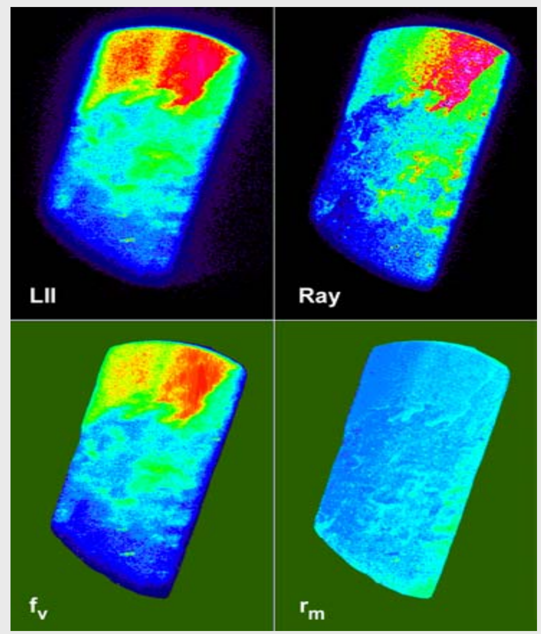
RAYLIX
Technique
-Test Bed Assembly-
-Single Shot Signals-



LII- and Rayleigh Signals
- Single Shot -

Engine speed: 1200 rpm; IMEP: 8 MPa

LII	0	1.5	3.0	4.5	6.0×10^4 Counts
Ray	0	0.5	1.0	1.5	2.0×10^4 Counts
f_v	0	1.0	2.0	3.0	4.0×10^{-7}
r_m	0	0.75	1.5	2.25	3.0×10^{-8} m



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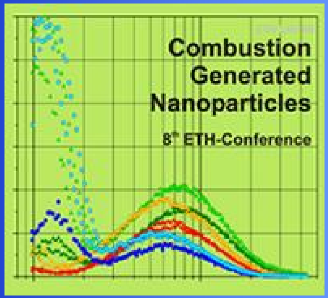
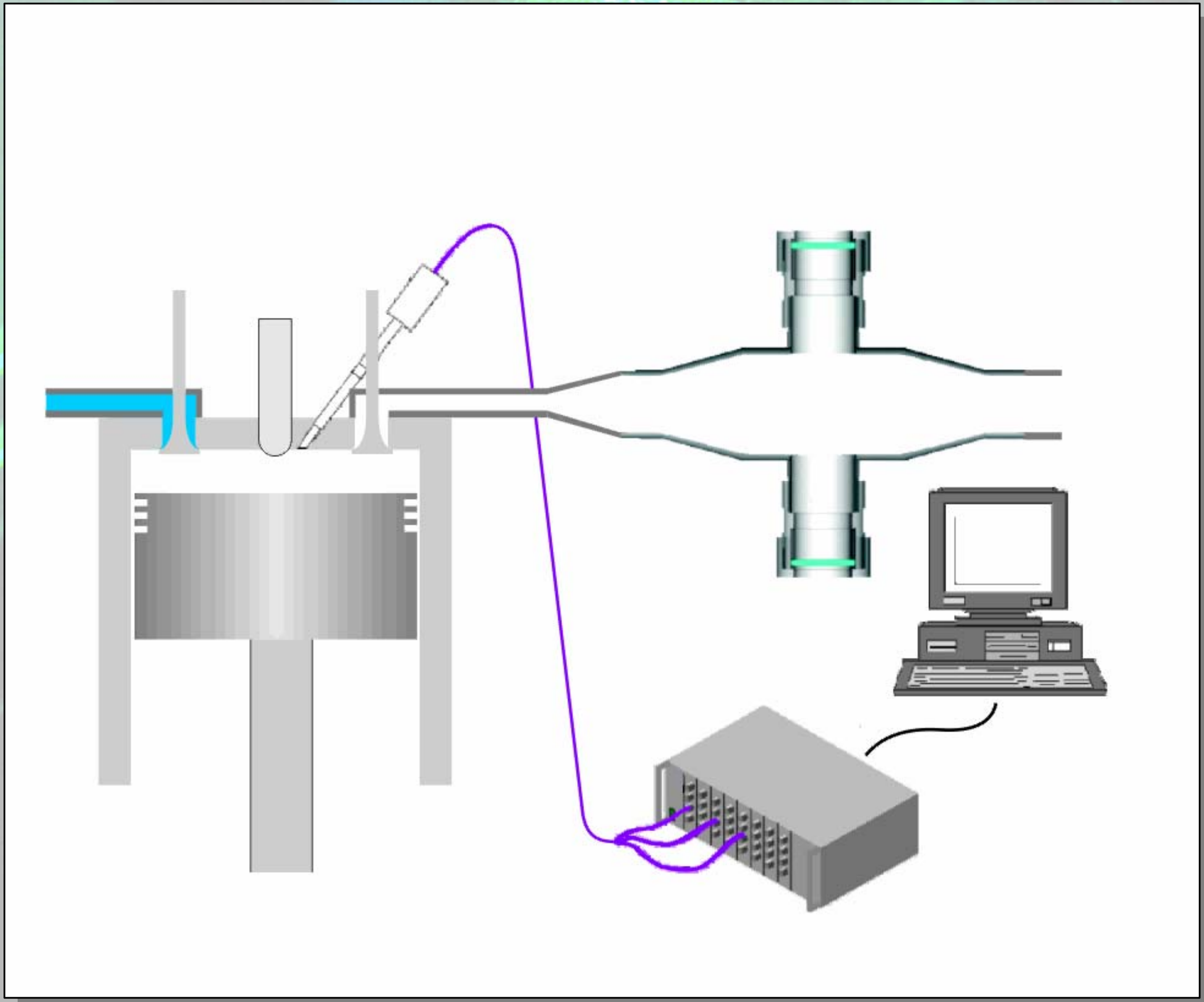


Experimental Set Up

RAYLIX
Technique
- Measuring Cycle -



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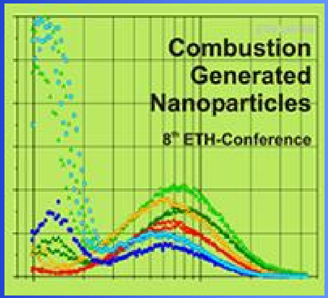

Experimental Results

Steady State Operation

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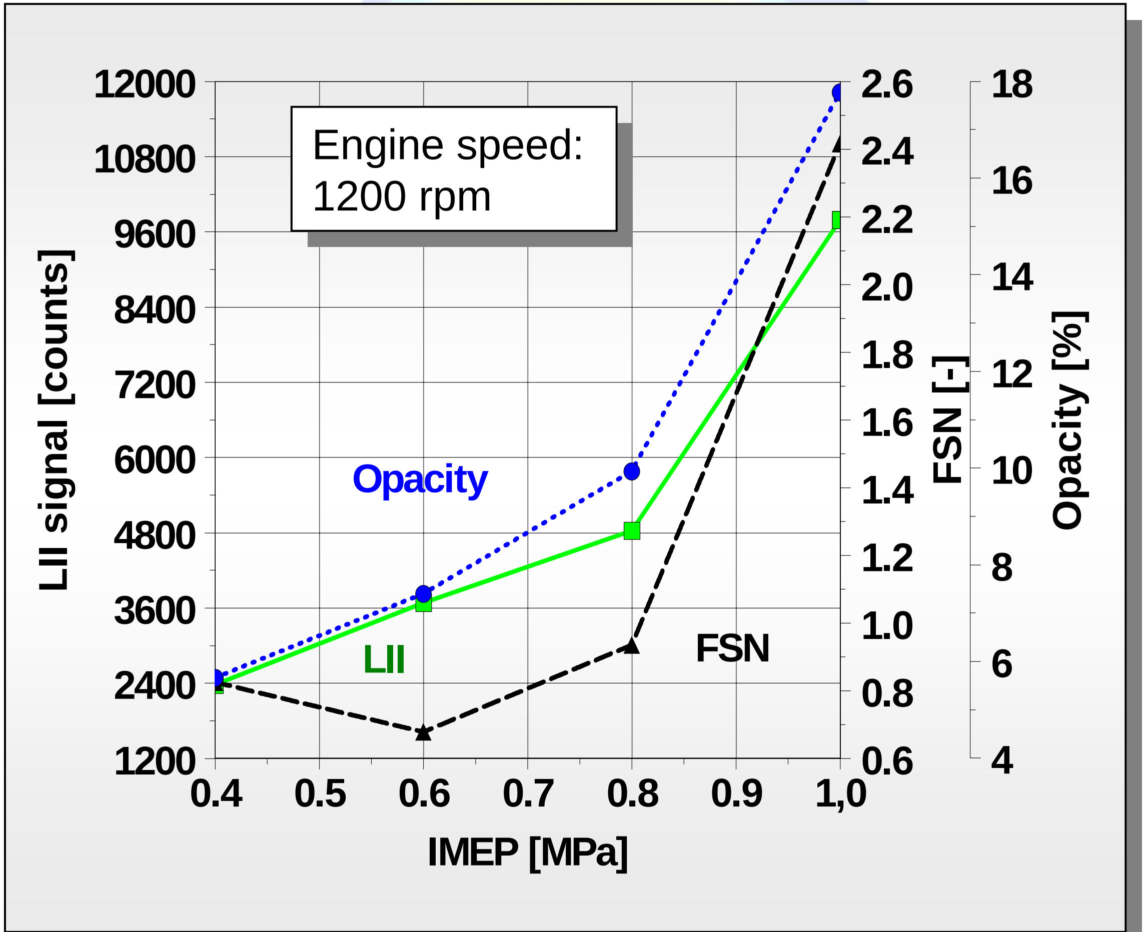
Comparison between LII, FSN and Opacity



Opacity enables calibration of relative LII signal to obtain absolute soot volume fraction f_V

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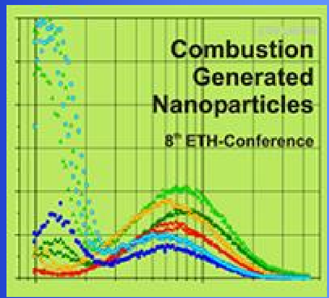
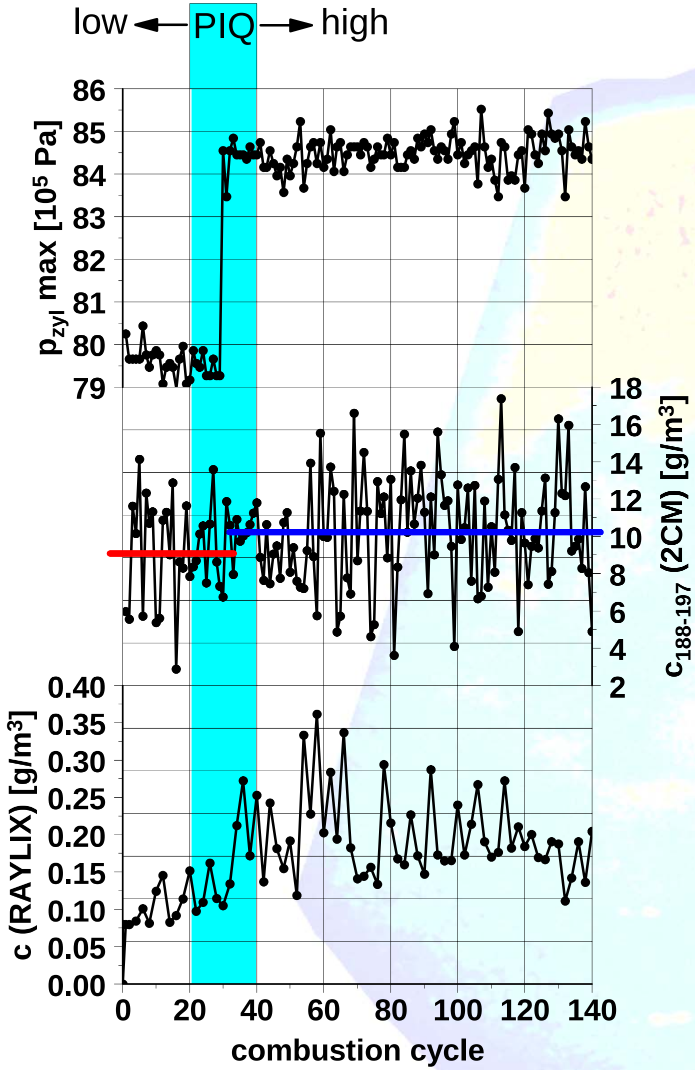
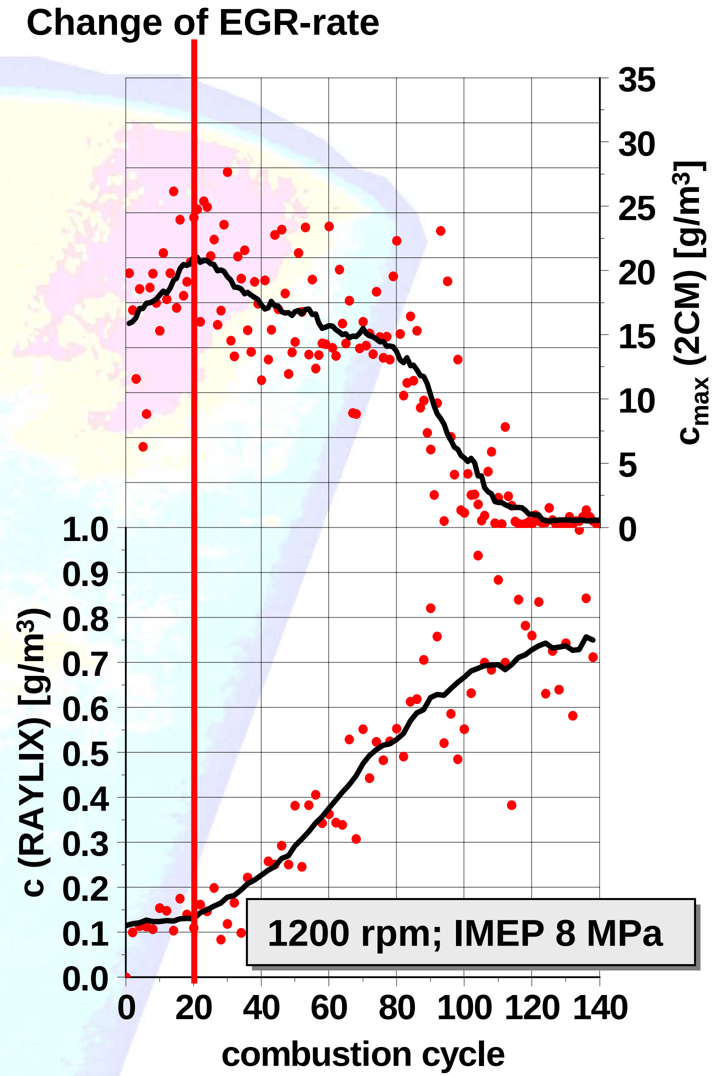


Experimental Results

- Variation of the Pilot Injection Quantity
- Variation of the EGR-rate





FSN: 0.93 -> 1.39
Opacity: 10% -> 13%

Engine Speed: 1200 rpm; IMEP: 8 MPa

FSN: 1.27 -> 4.28
Opacity: 11% -> 39%
FSN: 1.22 -> 3.92
Opacity: 12% -> 32%

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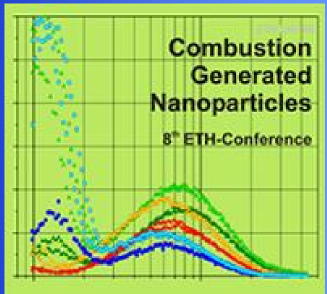
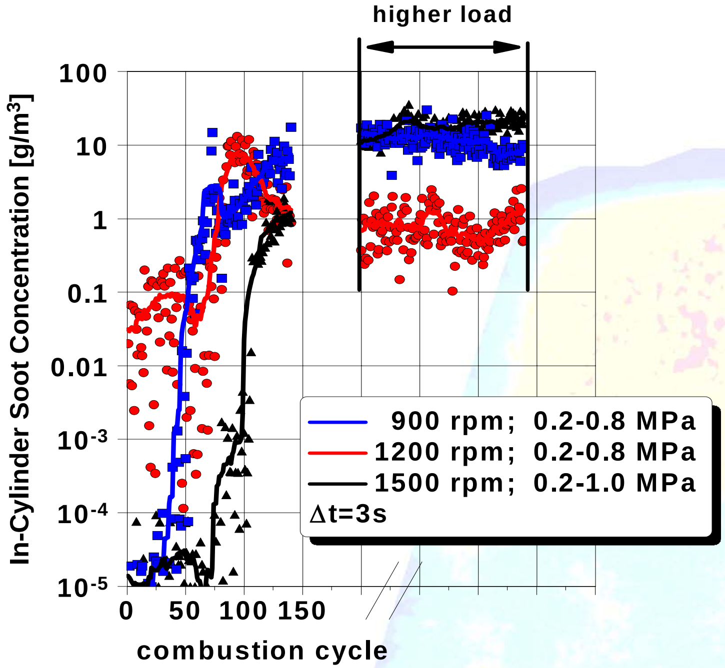
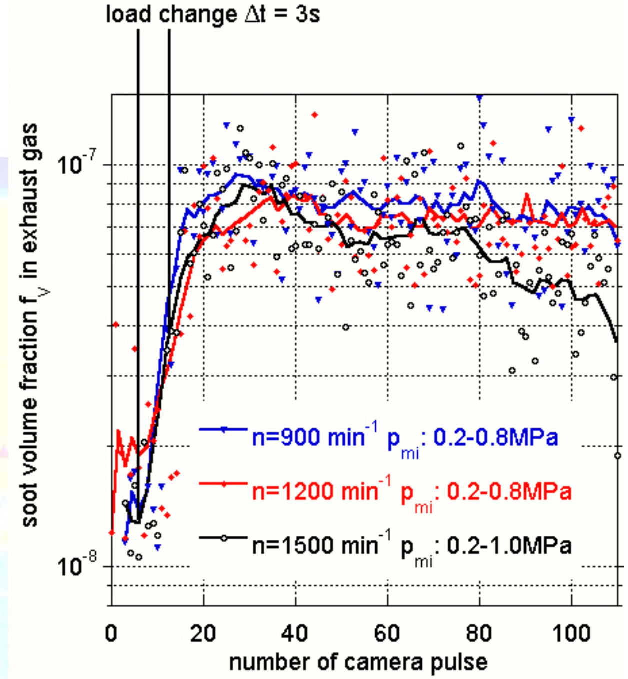
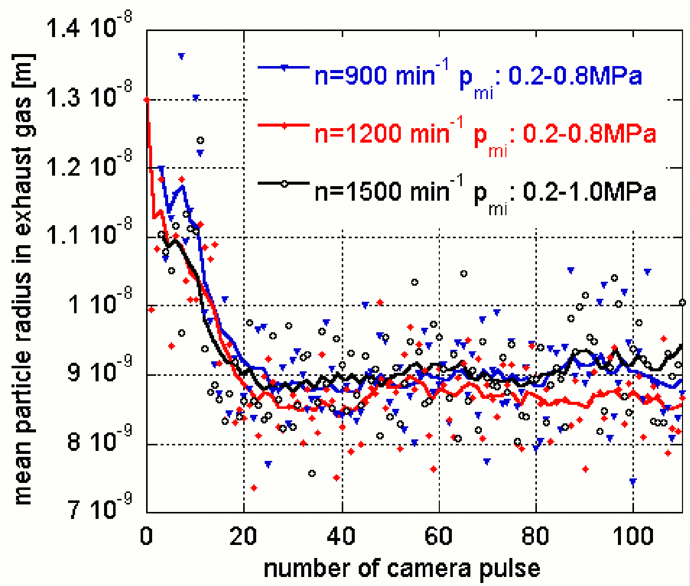


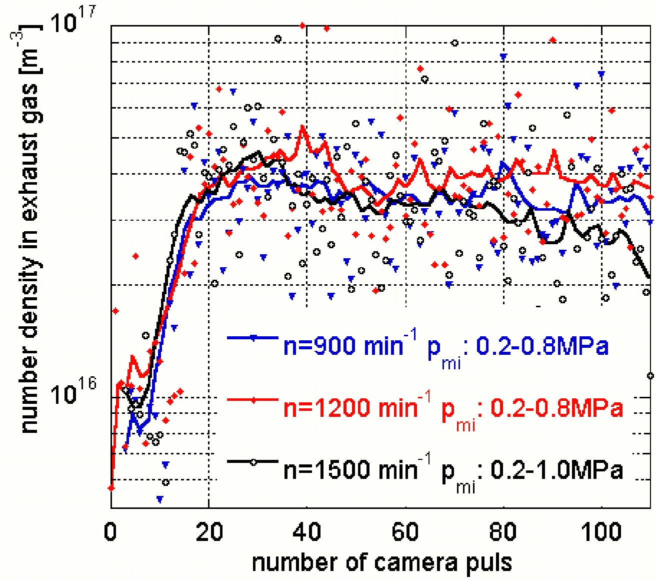
Experimental Results

Load Change with n=const.
900/1200/1500 rpm









FSN [-]:	**900: 0,6 ⇒ 2,2**	**1200: 0,96 ⇒ 1,49**	**1500: 0,9 ⇒ 2,5**
Opacity [%]:	**900: 3,0 ⇒ 15**	**1200: 4,00 ⇒ 9**	**1500: 4,0 ⇒ 18**

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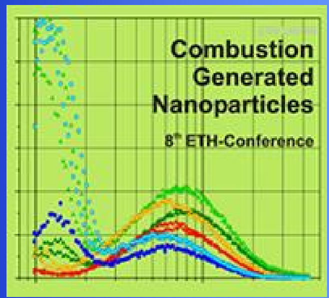
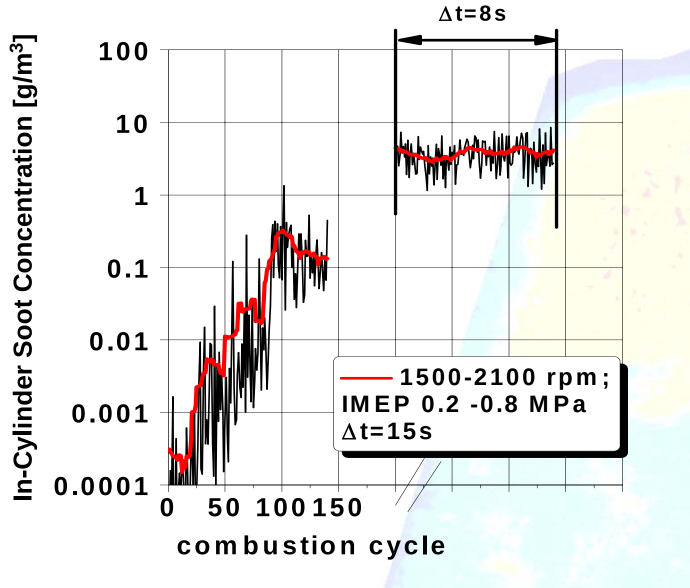
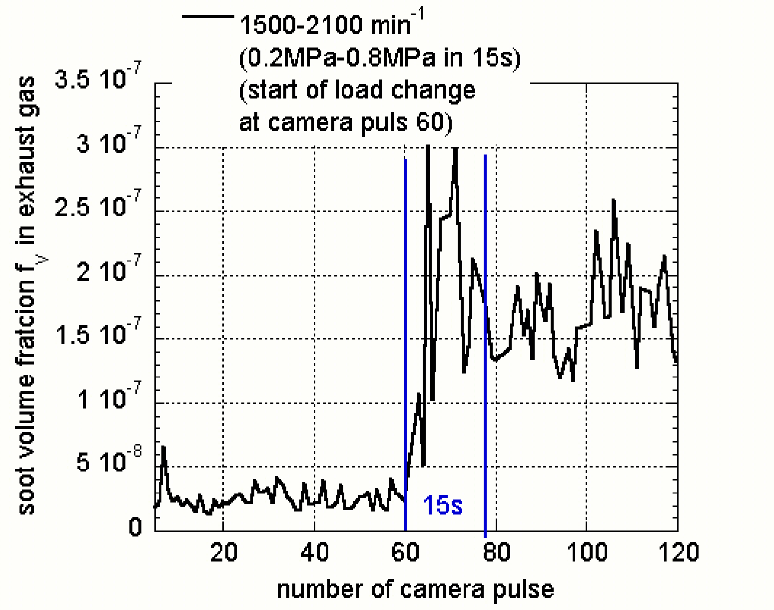
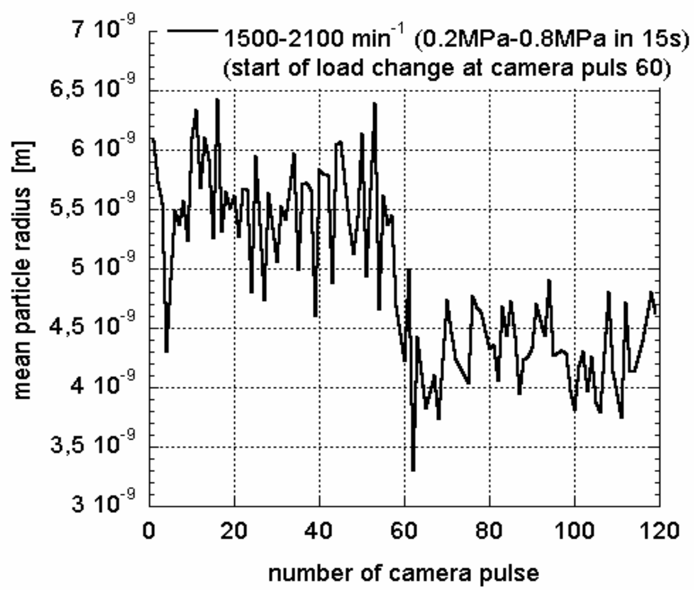


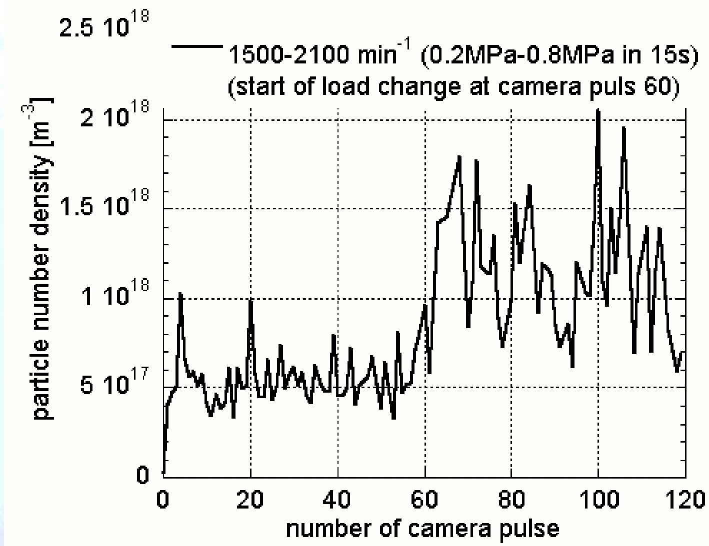
Experimental Results

Load Change with n≠const.
1500-2100 rpm









FSN [-]:	**0,3 ⇒ 0,6**	**Opacity [%]:**	**1 ⇒ 5**

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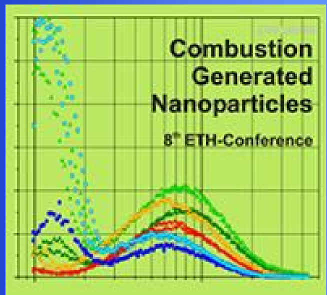
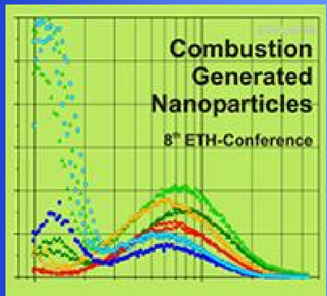


Conclusions

- Soot Concentration have been measured with Two Color Method and RAYLIX
- These techniques enable comparison of soot amount in the combustion chamber and in the exhaust gas
- RAYLIX also gives information on mean particle radii and number density
- At steady state operation FSN, Opacity and the averaged LII signal correlate well
- Rise of Pilot Injection Quantity causes increase of soot emissions in exhaust gas, in-cylinder soot concentration remains almost constant
- Rising EGR-rate causes decreasing in-cylinder soot concentration and increasing amount of soot in the exhaust gas



Conclusions

- Load changes with n=const. and n≠const. show similar behavior regarding soot concentrations, mean particle radii and number densities:
  - soot concentrations in combustion chamber and in exhaust gas are rising
  - mean particle radii decreasing
  - number densities increasing
- In the majority of cases higher engine speeds result in lower soot concentrations at different loads
- Load changes at higher engine speeds do not show those sharp increase in soot concentrations as load changes at lower engine speeds
- Basically soot concentrations in the combustion chamber and in the exhaust gas show similar tendency during load changes

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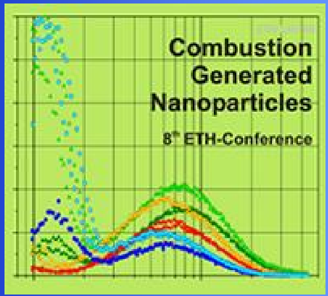

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Thank you for your attention!

Acknowledgements:

This study is funded within research program SFB 606 (“non-steady combustion”) by the
Federal Ministry of Education and Research, Germany (DFG)

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